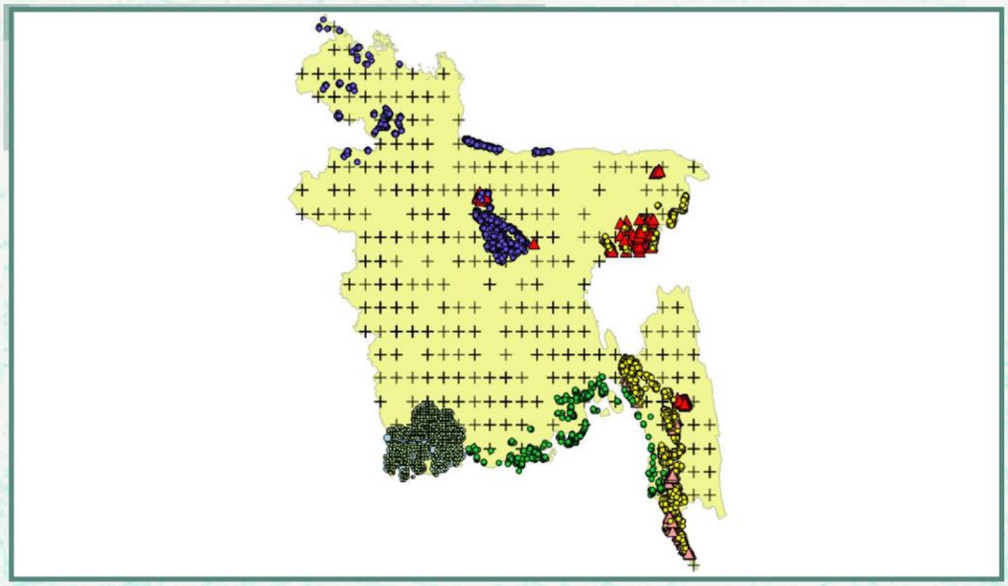
Forest Biomass in Bangladesh: An historical review of forest inventories to assist national estimates



Bangladesh Forest Department

November 2016

UN-REDD PROGRAMME

The UN-REDD Programme, implemented by FAO, UNDP and UNEP, has two components: (i) assisting in developing countries to prepare and implement national REDD strategies and mechanisms; (ii) supporting the development of normative solutions and standardized approaches based on sound science for a REDD instrument linked with the UNFCCC. The programme helps empower countries to manage their REDD processes and will facilitate access to financial and technical assistance tailored to the specific needs of the countries.

The application of UNDP, UNEP and FAO rights-based and participatory approaches will also help ensure the rights of indigenous and forest-dwelling people are protected and the active involvement of local communities and relevant stakeholders and institutions in the design and implementation of REDD plans.

The programme is implemented through the UN Joint Programmes modalities, enabling rapid initiation of programme implementation and channelling of funds for REDD efforts, building on the in-country presence of UN agencies as a crucial support structure for countries. The UN-REDD Programme encourage coordinated and collaborative UN support to countries, thus maximizing efficiencies and effectiveness of the organizations' collective input, consistent with the "One UN" approach advocated by UN members.

The UN-REDD Bangladesh National Program is implemented by the Bangladesh Forest Department under the leadership of Ministry of Environment and Forests. United Nations Development Program (UNDP) and Food and Agriculture Organization (FAO) are the two implementing partners.

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1 INTRODUCTION

A number of forest inventories have been conducted in Bangladesh, for different objectives, with different capacities and at various geographic scales (Bangladesh Forest Department, 2007; Latif, Chowdhury, & Netzer, 2015; Revilla, Ahmed, & Mabud, 1998a; Sylvander, Latif, & Karlsson, 2001). While the data collected have been used for specific purposes, the use of those data to support common, national objectives has not been fully explored.

A compilation of this historic data may be useful to increase knowledge of the status of the national tree and forest resource and to assess volume, biomass, carbon stocks and emission factors to support the preparation of the Greenhouse Gas (GHG) inventory and report national communications to the United Nations Framework Convention on Climate Change (UNFCCC). However, complexities related to data harmonization must be addressed to ensure data meets the standards of transparency, consistency, comparability, completeness and accuracy defined by the UNFCCC. In order to present a robust and complete review of the available data, a comprehensive data cleansing process was undertaken. This process highlighted the susceptibility of data to the many sources of error and bias that can influence results throughout the data management process, from data collection, entry, processing, analysis and reporting.

This report outlines methodologies used to harmonise seemingly disparate datasets, derived under different methodologies, with different definitions and data collection variables. It included an overview of methods used to model tree height, volume and biomass using local and international data and compares two methods for estimating biomass using different input variables.

The objectives of this report therefore, are to (1) document methods used in past forest inventories in Bangladesh, (2) present the methodology and results of the harmonization inventory data, (3) to prepare tree and forest carbon stock and stock changes, and (4) prepare the data for their integration with the 2015 land cover map by harmonizing land cover classes with the national land cover/use reference system.

2 AN OVERVIEW OF EXISTING FOREST INVENTORIES IN BANGLADESH

2.1 Main characteristics of the historical inventories

Bangladesh has a long history of forest inventory with multiple assessments being carried out for different purpose, at different scales. The first documented survey was conducted in the Sundarbans between 1769 – 1773 with the dual purpose of surveying forest stocks and waterways (Iftekhar & Saenger, 2008). Seven additional surveys were carried out in the mangrove belt between 1821 and 1964 (see Appendix 1) and after the 1960's inventory projects were conducted in the Sundarbans, Chittagong and Chittagong Hill Tracts, Sylhet and the coastal regions. The first national inventory was undertaken between 2005 – 2007 (BFD, 2007).

The impetus for conducting a forest inventory has evolved over time. Historically, the objectives focused on quantifying the timber resource, often for a specific purpose such as to service pulp mills (Forestal, 1960). More recent inventories have been carried out in Reserved/Protected Forests and National Parks with a focus on conservation management, carbon assessment. In 2007, the first national forest and tree resource assessment was carried out in Bangladesh to monitor land use dynamics over time.

Several sampling options and plot shapes were used during the past inventories. The plot shapes are designed to reflect the specific environmental context, objectives and capacities of its inventory. Circular plots have been preferred in forest plantations for timber assessment as well as in natural forests for carbon inventory or other, generally, narrow range of parameters. Rectangular shapes were applied in the nationwide inventory or in some natural forests across the country. This latter plot shape has the potential to generate reliable observations of land use with relatively fewer plots on the ground when large plot shapes are applied, such as in the 2007 national assessment and in this way explore trends and variations of forest and land use. The use of data from previous forest assessment is determined by the availability of documentation of the survey design and methodology and the appropriate archiving of data.

Data from six projects were available with adequate documentation to be considered for this harmonization exercise. The inventories spanned across 18 locations and were implemented under various partnership arrangements, with different objectives and scope. Table 1 presents an overview of the data available for the study.

Table 1: Overview of available data for consideration in the harmonization study.

Project	Inventory	No. of measured plots	No trees	Plot Shape	Nested subplot	Min dbh (cm)	Max dbh (cm)	Level 1 Condition	Level 1 shape	Level 1 area (ha)	Level 2 condition	Level 2 shape	Level 2 area (ha)	Level 3 condition	Level 3 shape	Level 3 area (ha)	Tree height measured
FRMP 1997 (FD-97-hill, FD-97-coastal, FD-97-Sund)	Forest Resource Management Plan comprising of three inventories in the sundarban, hill and coastal areas.	7511	276339	circle	yes	0.9	120	DBH >10 cm	11m radius (5 times)	0.19	-	-	-	-	-	-	partial
FD-01-SAL	Forest inventory of the Sal forests of Bangladesh in Dhaka, Tangail and Mymensingh / Dinajpur, Rangpur and Rajshahi	3693	23809	circle	no	9	75	DBH >10 cm	5.64/7.98m radius (6 times)	0.06/ 0.12	-	-	-	-	-	-	partial
FD-07-NFA	Forestry department National forest assessment	251	38993	Rectangle	no	3	231	DBH >10 cm	250m x 20m (4 times)	2	DBH: <10 cm	3.99 radius (3 times)	0.02	-	-	-	all
FD-10-SundRF	Carbon Assessment Inventory Of The Sundarbans Reserved Forest	150	22034	circle	no	0.1	170	DBH >10 cm	10m radius (5 times)	0.16	DBH: <10 cm	3 radius (5 times)	0.01	-	-	-	partial
CREL-10	Bangladesh REDD+ARR Protected Areas Project (2010)	300	6398	circle	no	10	122	DBH >10 cm	17.84m radius (5 times)	0.1	DBH: >10 cm -	10 radius (5 times)	-	-	-	-	partial
CREL-14	Carbon Assessment Inventory of 8 Pas (2014)	213	1741	circle	yes	50	68.5	DBH >50 cm	17.84m radius (5 times)	0.1	DBH: >20 cm	10 radius (5 times)	0.03	DBH: >5 cm	4 m radius (5 times)	0.005	Sample

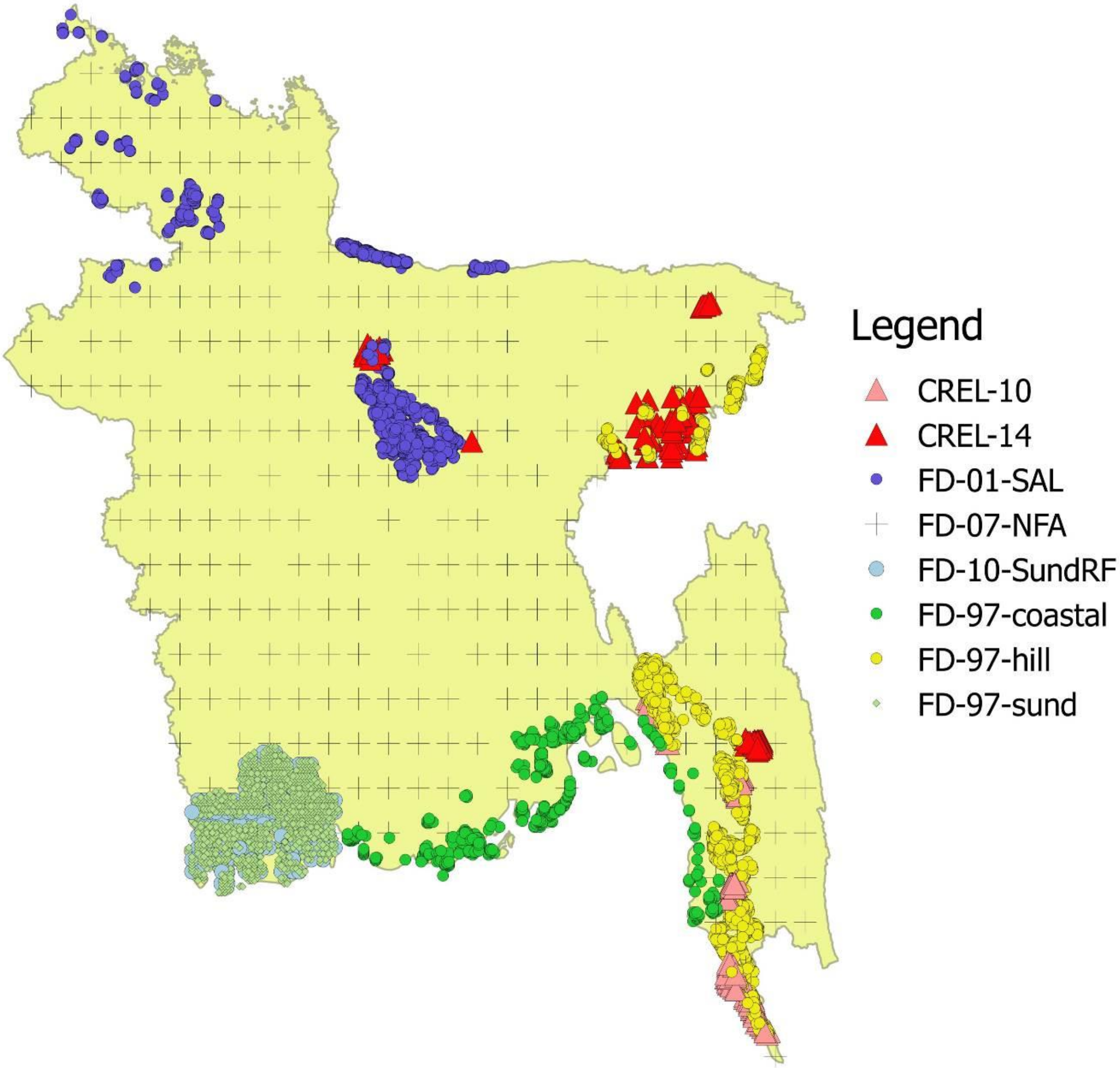

Figure 1: Geographic location of field inventory plots used in the study.

2.2 Detailed presentation of each inventory campaign

Forest Resources Management Project (FRMP) 1998

The FRMP was a World bank funded initiative implemented in the Coastal afforestation divisions, Sundarban Reserved Forest and the natural and plantations forests of Chittagong, Cox's Bazar and Shylet Forest Divisions.

The primary objective of the FRMP was to generate information on the standing timber resource to assist planning of integrated management initiatives. A dedicated bamboo inventory was carried out as part of the FRMP however the data has not been included in the harmonisation process. Secondary objective were to provide time series data where possible and to establish, or at least provide a basis for establishing, permanent sample plots in targeted forest areas, however a follow up inventory based on this sample design never eventuated. The results of the inventory are presented in three reports and often discussed separately throughout this report in terms of the Hill, Coastal and Sundarbans context.

The sample unit is a cluster of five plots where with nested sub-plots, one sub-plot each for seedlings (1 m radius), saplings (2 m radius), poles (5 m radius), and trees (11 m radius). The plots are spaced 50 meters apart in initiated from the central plot. In the Sundarbans, the sub-plot number is reduced to three in areas of Golpatta which are predominantly found along the river banks.

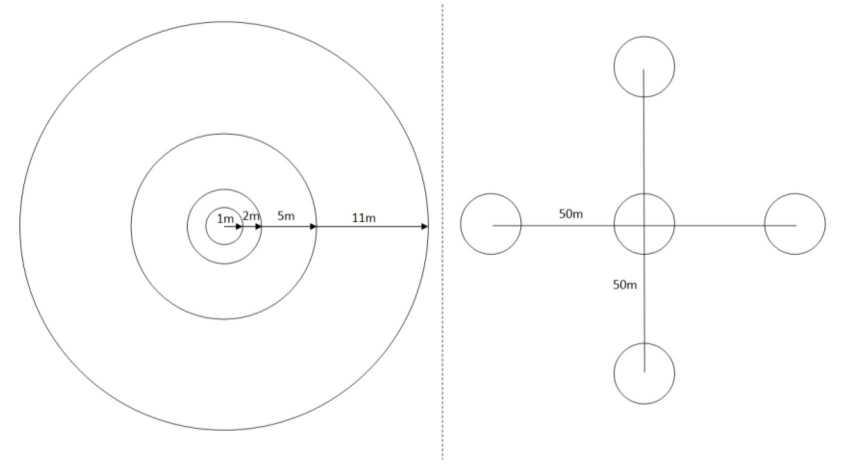

Figure 2: Plot design of the FRMP inventory.

A total of 7,511 plots were measured capturing 276,399 trees. Tree heights were measured for approximately 38% of trees however this was variable across the forest types. Tree heights in the hill and coastal areas were measured 58% and 62% of the time respectively, while in the Sundarbans they were measured for only 21% of trees. The rationale for the variable height measurement has not been determined because details of the sampling design specified in the "first fielding report of the Forest Inventory Specialist" (Junc 1995), has not been located. Information related to survey design and variables lists have been garnered from the reports.

Forest inventory of the Sal forests of Bangladesh 2001

The Sal forest inventory was implemented by the Forestry Department to better understand the distribution, regeneration and potential production of Sal forest and to inform management decisions (FD, 2001).

Field data was collected between November 1999 and May 2000 in the Sal forests areas of Dhaka, Tangail, Mymensingh, Dinajpur, Rangpur and Rajshahi Divisions. A systematic sampling design was adjusted in different areas to maximize the sampling efficiency. Sampling lines were spaced 400 m apart (except for Tangail Division were they were 500 m apart) with 200 m between circular volume plots along each line. Plots were 100 m^2 in area in Dhaka, Tangail and Mymensingh Divisions and 200 m^2 in area in Dinajpur, Rangpur and Rajshahi Divisions. A total of 5287 volume plots were sampled on forest land.

Tree heights were based on a sample where by the two trees (one, the largest and two, at random) were measured with a Suunto or hypsometer.

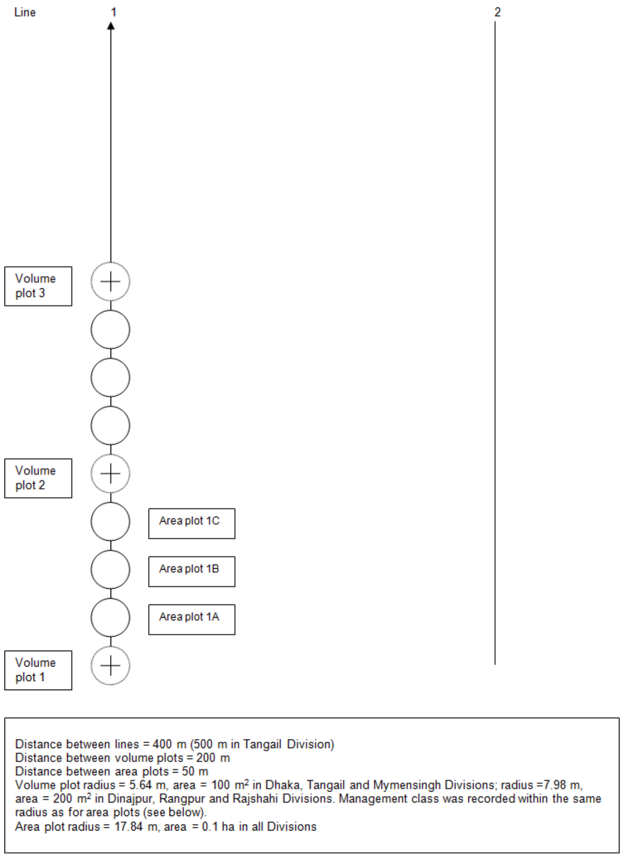

Figure 3: Plot layout of the Sal inventory

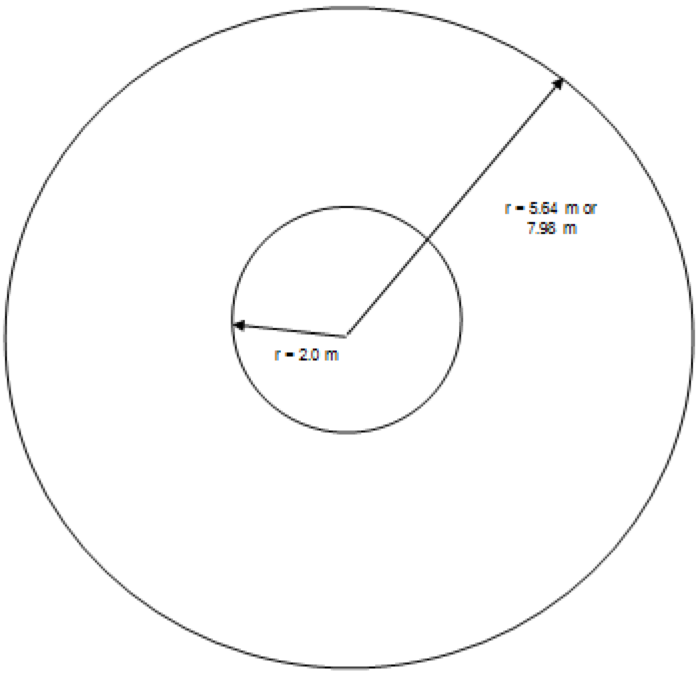

Figure 4: Schematic diagram of volume and regeneration plots

National Forest and Tree Resource Assessment 2005-2007

The National Forest and Tree Resource Assessment (NFA) was the first national scale inventory in Bangladesh and was intended to provide a protocol for ongoing, periodic measurement to assess changes in land use and tree and forest resources (Bangladesh Forest Department, 2007).

The sampling design and plot layout followed FAO's then standard, global approach which consisted of systematic sampling with each unit being designated as a 'tract'. Each 1km x 1 km tract consisted of four plots four 250 m x 20 m plots in which the actual field measurements were are carried out. In Forest plots, circular subplots (3.99 m diameter) were measured for seedling/sapling regeneration. The subplots were established at their centre at 5 m, 125 m and 245 m from the Plot starting point along the Plot central axis (FAO, 2005).

A total of 299 tracts were established of which 251 were measured, encompassing 38,988 trees.

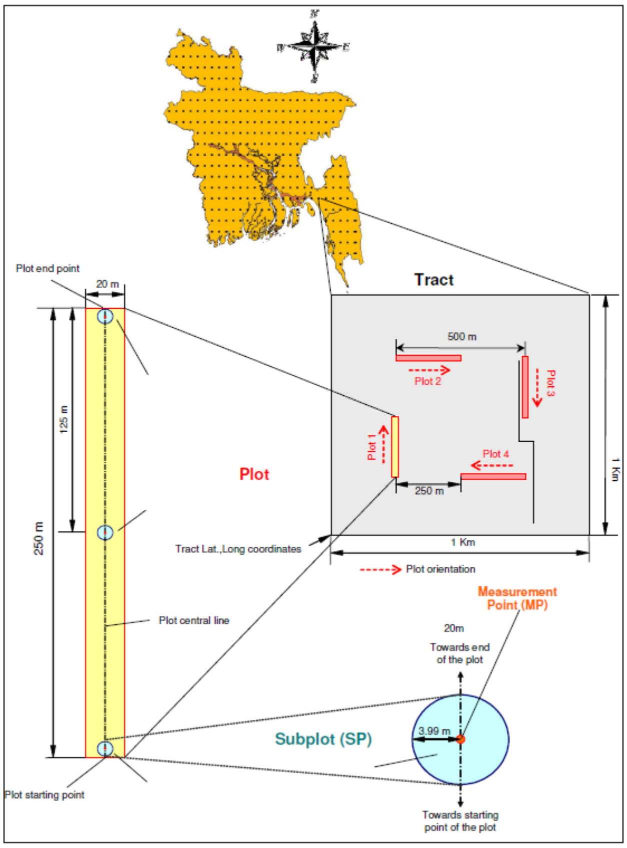

Figure 5: Plot design of the NFA.

Carbon Assessment Inventory of the Sundarbans Reserved Forest - 2009-2010

This assessment (hereafter FD-10-SRF) was supported by USAID with technical assistance from the US Forest Service. The assessment used C stocks from the FRMP 1997 Sundarbans inventory (FD-97-Sund) to estimate C stock changes with the intention to develop emissions factors and inform reporting requirement under REDD+ (Donato, Ahmes, & Iqbal, 2011).

The inventory design sub-sampled the plot grid developed under the FRMP assessment and located 155 plots by selecting every second plot in both X and Y directions (Donato, Kauffman, & Stidham, 2009). A total of 22,034 trees were recorded. It was proposed to establish permanent sample plots for periodic re-measurement however due to project constraints tree tags were not used and permanent plots were never actualized.

Tree height was estimated based on a sample methodology where by three trees representing the dominant canopy height were measured with a clinometer or laser/hypsometer and extrapolated as an average for the plot.

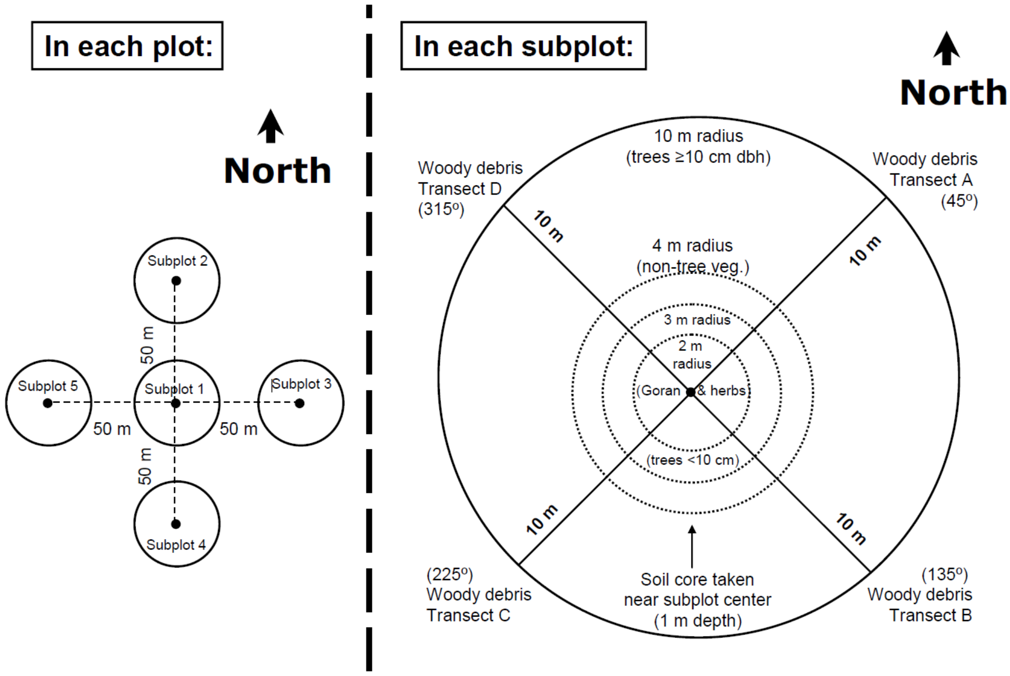

Figure 6: Plot design of the FD SRF inventory.

Bangladesh REDD+ afforestation, reforestation and revegetation Protected Areas Project (CREL) 2010

The CREL 2010 project, funded by USAID, conducted inventories in six protected hill forests areas in south-eastern Bangladesh (GoB, 2011). The inventories were designed to estimate carbon stocks to support reporting under REDD+.

Similar to the FD-10-SundRF carbon assessment, the inventory maintained a circular plot cluster developed with support from the US Forest Service on both occasions. The field manual for this inventory was printed in Bangla only and no translation has been made available to contribute to this report.

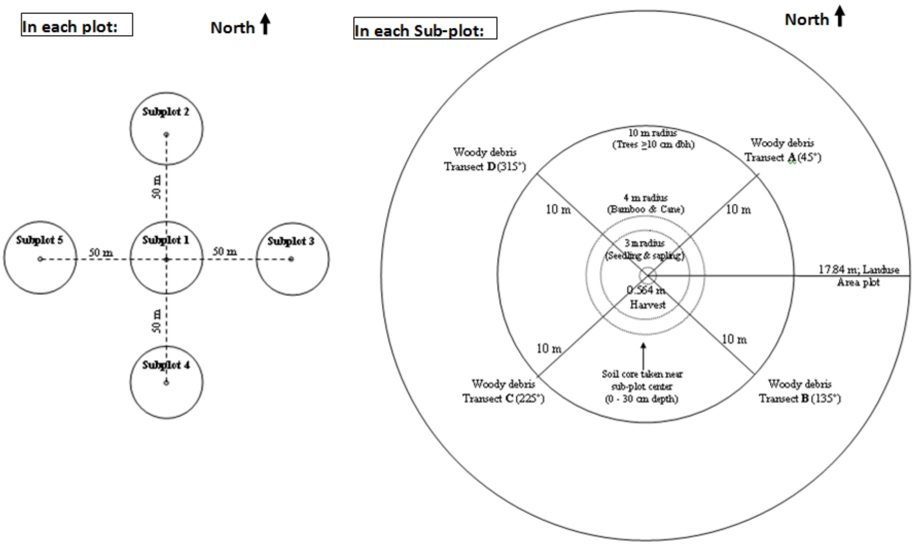

Figure 7: Plot design and layout of the CREL 2010 inventory.

Climate-Resilient Ecosystems and Livelihoods (CREL) 2014

The USAID funded CREL 2014 project conducted carbon inventories in eight protected areas. Khadimnagar National Park (KhNP), Lawachara National Park (LNP), Satchari National Park (SNP), Rema-Kalenga Wildlife Sanctuary (RKWS), Modhupur National Park (MNP), Kaptai National Park (KNP), Chunati Wildlife Sanctuary (CWS) and Himchari National park (HNP) (Fakir, Netzer, Banik, & Chowdhury, 2015).

The plot design built on previous work implemented with the US Forest Service with a nested circular plots design laid in a systematic grid at 30”X30” intervals. Data was recorded at 2 m, 4 m, 10 m and 17.84 m radii plots.

Tree height was measured on up to three trees per plot including two “co-dominant” (or average) trees.

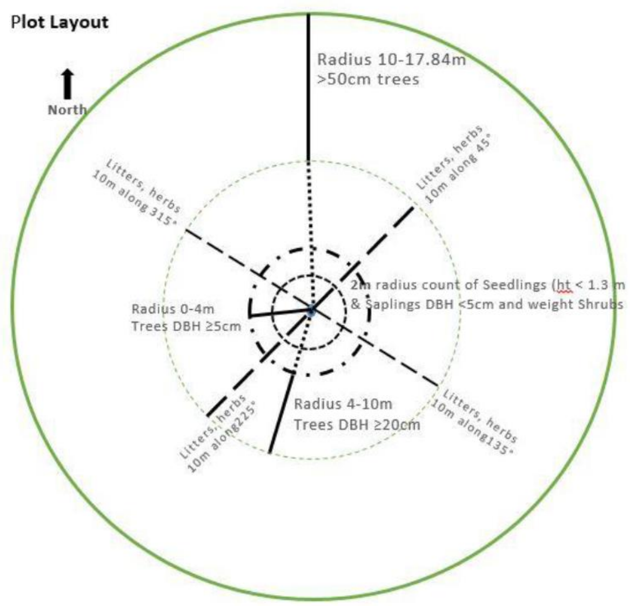

Figure 8: Plot layout of the CREL inventory.

3 METHODOLOGY

3.1 Harmonization of the databases

Plot information from all available inventories was harmonised into a single dataset. The final database represents common variables across the inventories. This includes unique tree id, original id, project/implementing entity, original file name, year, plot id, subplot id, plot coordinates, district, land use, forest type, scale, topography/slope, soil, plot size (ha), scale factor, botanical name (Genus, Species, Local), dbh (cm) and height (m).

Numerous data errors related to GPS coordinates, height, dbh, botanical names were identified and corrected where possible or removed from the data set. Errors related to GPS coordinates included basic data entry errors where one or multiple numbers were incorrect, or x and y values were swapped. Some plots listed more than one geographic coordinate for the one plot location, in which case the maximum coordinate value was used. Errors were identified in QGIS and rectified in an R script.

Erroneous or unrealistic height values (>100m, <0) were corrected as NA. A similar process was undertaken for DBH values, with a threshold of 300 cm, noting that trees of the genus *Ficus* can feasibly reach those diameters. Trees with unrealistic height – diameter relationships were assessed on a case by case basis. Also, numerous DBH measurements recorded outside of the appropriate subplot dimension were removed from data set. Species names were corrected through the Taxanomic Names Resolution Service and discussed further below. Table 2 provides an overview of the types of errors removed from the data before analysis.

Table 2: Tree records removed for analysis

Project	Total trees per inventory	Missing dbh	dbh outlier or incorrectly measured	h not measured (*)	h outlier	Species name missing	Number of trees used for the data analysis	Number of trees used for the tree H-D relationship	Number of trees used to validate the H-D model
FRMP (1997)	276339	0	1	179200	8655	63280	276399	70109	18435
FD-01-SAL	23809	0	0	14697	0	0	22009	5857	1455
FD-97-NFA	38993	5	9	14	568	105	38979	28292	10119
FD-10-SRF	22034	501	2905	19994	0	18716	18716	1581	459
CREL-10	6398	413	464	4231	3	2625	5433	1878	286
CREL-14	1741	0	365	1742	0	355	1376	72	13

3.2 Land cover classes

Land cover classes differed across each inventory. The NFA, which was highly focused on land use change detection and obviously national in scale, had 32 classes, including 12 forest types. The Sal forest inventory described eight classes including four maturity levels from young to mature, in addition to 'Agroforestry', 'Woodlot', 'Private encroached' and 'Grass - degraded former forest land' (see Appendix 2 for a list of Land Classes per inventory).

Land class descriptions were available for the CREL-14 and NFA-07 projects, however no further description was provided or available for the other projects beyond the class name. The absence of detailed land cover descriptions has implications for the comparability between different projects. This is particularly problematic when attempting to detect changes over time.

Fifty-five different land use classes are used in the harmonized data set. Each class was harmonized with the National Land Cover Reference System of Bangladesh (in Prep). The 55 land classes corresponded to 23 classes within the national reference system. The hierarchical structure of the national reference system was used to eliminate ambiguity in the classes. For example the NFA class "Long rotation forest plantation: 40-60 years (Teak, Dipterocarp, Sal etc.)" could not be differentiated based on rotation length as the national reference system differentiates on phenology at the lower class level than long/short rotation. The class was therefore translated as "Cultivated Forest Plantations (Terrestrial)" (see Figure 9).

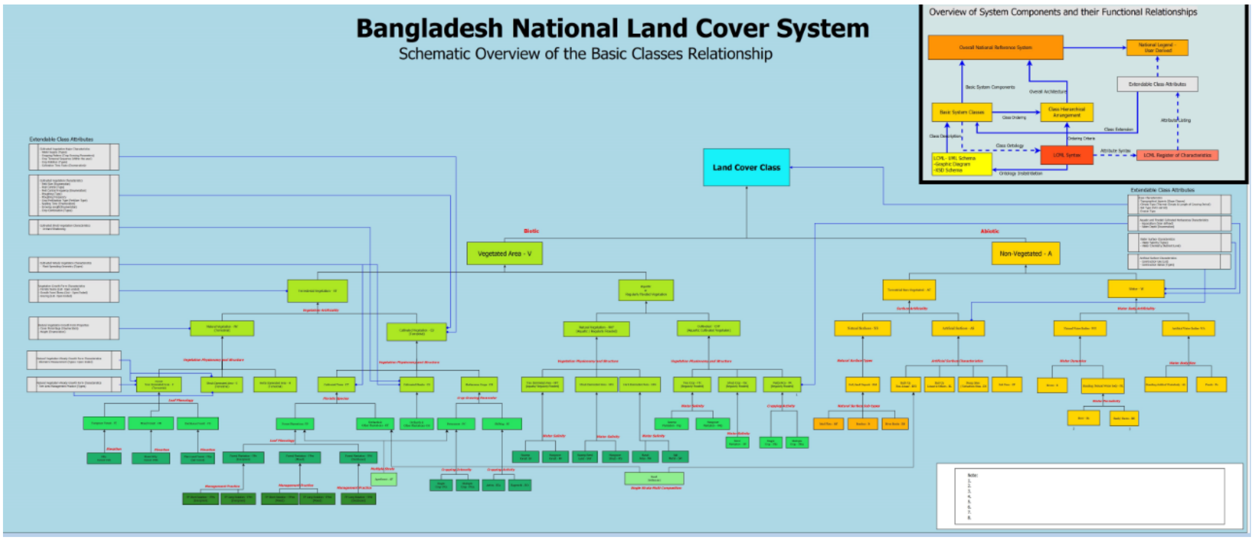

Figure 9: The national reference system of land cover classification of Bangladesh.

Trees that had multiple or conflicting land classes could not be harmonized for example "Bare Land" and "Agriculture". In some cases this occurred where more than one land classes was assigned at plot level. As a result, all land classes observed are assigned to all trees in the plot. Similarly, the class "Grass/Bare Ground" in the FD-10-SundRF inventory could not be harmonized as it crosses the two highest level classes of "Vegetation Areas" and "Non-Vegetated". A full list of land use classes and their corresponding class according to Bangladesh's National Reference System is provided in Appendix 3.

3.3 Broad forest type

Six broad forest categories were created to assist data analysis. The categories, outlined in Table 3, were assigned to each tree record based on the scope and geographical context of the project, and where possible, the land use classification assigned. For example all trees from the CREL inventories were assigned within the broad forest type "Hill forest" (except trees within Modhupur National Park which are considered as "Sal forest"). Trees in the FRMP-97 inventory were assigned a broad forest type category that reflected their respective project areas of coastal, hill and Sundarban. Similarly, all trees in the Sal 2001 inventory were assigned as Sal Forest. It is important to note that these categories are based on a geographical context as opposed to an actual land use class. In the case of the NFA-07 however, the land use category was interpreted based on the expert judgment. A breakdown of the number of plots measured in each forest type is provided in Table 3 .

Table 3: Number of plots per broad forest type.

Forest Types	CREL-10	CREL-14	FD-01-SAL	FD-07-NFA	FD-10-SundRF	FD-97-coastal	FD-97-hill	FD-97-sund
Bamboo or mixed bamboo/forest	0	0	0	9	0	0	0	0
Coastal forest	0	0	0	1	0	610	0	0
Hill forest	300	157	0	30	0	0	3208	0
Non forest	0	0	0	222	0	0	0	0
Sal forest	0	49	3693	2	0	0	0	0
Sundarbans forest	0	0	0	6	150	0	0	1202

3.4 Correction of species names

Inconsistencies between species names were rectified using the Taxanomic Name Resolution Service available online through the iPlant Collaborative TNRS Application (http://tnrs.iplantcollaborative.org/). The application processes species lists that are uploaded in text file format. A consolidated list is returned, matching the name submitted with the correct ISBN nomenclature. An overall score (0-1) is assigned to assist detection of ambiguous names and spelling errors. In the vetting process, names that scored below 0.95 were individually queried and processed through the Plant List online database (http://www.theplantlist.org/).

No species information was available for the Sundarbans Carbon Assessment.

3.5 Identification of wood density values

Wood density values were derived from DRYAD's Global wood density database (Zanne et al., 2009). The database provides 16,468 wood density values for 8,412 species which are differentiated by 16 different regions. The database was filtered for values from India, South-east Asia, and Tropical South Asia and the average wood density was used.

Wood density values were assigned based on scientific name, using a four tiered methodology preferencing species, genus and family in consecutive order. If no match was found at the lowest (family) level the tree was assigned the average of all values from all species from the regions mentioned above. On average, 1.95 samples were present at species level, 9.78 at genus level, 86.2 at family level and the wood density of 4156 species were averaged for the generic value of 0.578 assigned in the absence of a species match.

3.6 Tree heights and height-diameter relationship modeling

Tree height can be a useful parameter for estimating biomass however accuracy can often be highly variable and in many cases inventories rely on models to estimate height based on trunk diameter. In the harmonized data set, individual tree heights were measured for 149,436 (approximately 60%) of trees. This data was used to develop a tree height-diameter relationship for the main forest types of Bangladesh and validate it. The overall procedure used was non-linear model with Maximum Likelihood, applied with the nlme() command in R software. A random effect of the FAO biomes and forest type was tested on the model parameters. A 10% sample was extracted from the dataset of tree diameter and height to test the model against.

Table 4: Proportion of tree heights measured in different inventories

CREL 2010	CREL 2014	NFA	FRMA	Sal	FD SRF
47%	7%	99%	32%	33%	9%

3.7 Development and selection of models for biomass calculation

3.7.1 Selection of tree allometric equations for volume and biomass assessment

Over 500 allometric equations are available for Bangladesh however many are untested and their reliability may be variable. A recent review by Hossain and Siddique (2016) validated 222 equations for 39 species of which four species represented almost 40% of the sample. Indeed the breadth of available, country specific allometric equations is limited in respect to the number of species identified in a forest inventory process. Moreover, the majority (>70%) of equations available are for volume only with only 6% available for oven dried biomass, and none are available for palm or bamboo. As a result only 2.5% of tree species known in Bangladesh have verified equations for estimating volume and biomass. Therefore, general biomass equations have been used as described below.

3.7.2 Biomass calculation

Two methods were used to estimate above ground biomass (AGB). Method 1 uses the IPCC default allometric equation for tropical moist forest (IPCC, 2003). This method relies on DBH as the only input parameter and is therefore the simplest method applied. The model is applied in two climatic zones in Tropical moist hardwoods and Tropical wet hardwoods. These were linked to the FAO ecological zones Tropical moist deciduous forest and Tropical forest respectively. The models applied are:

$$Tropical\ moist\ hardwoods: AGB = exp(-2.289 + 2.649 * log(DBH) - 0.021 * (log(DBH))\text{^}2)$$

$$Tropical\ wet\ hardwoods: AGB = 21.297 - 6.953 * (DBH) + 0.740 * (DBH)\text{^}2$$

where AGB is the aboveground biomass in kg and DBH the diameter at Breast height in cm.

Method 2 was was calculated using the Chave et al. (2014) based on tree DBH (cm), height (m) and species' wood density (WD, g.cm-3)

$$AGB = 0.0673 * (dbh\text{^}2 * h * wd)\text{^}0.976$$

If tree height was not available from the data the local model developed for Bangladesh's broad forest type was used.

4 RESULTS

4.1 Species distribution and frequency

The attributes for 369, 378 trees have been harmonized into a single data set. The trees are represented from 9,936 plots, across two global agro-ecological zones. Almost 60% of trees were measured in the FAO ecological zone ‘tropical moist deciduous forest’, the rest was located in the ‘tropical rainforest’ zone. Over 40% of the data was collected in the Sundarbans forest that was mainly on account of the FRMP 1997 inventory which measures 1,202 plots.

A total of 314 species from 226 genera were represented in the sample. Botanical information was provided for 65% of trees however this was variable across the sample. Given that inventories have been carried out in all major forest types this is unlikely to influence the results.

Table 6 and Table 7 show the most common genus and species found in Bangladesh as a proportion of the entire dataset (including trees without identified species) and the top 10 species per broad forest type are provided in Appendix 4. Species identification was poorest in the hill areas, however this is influenced by the CREL 2010 project’s low ID rate.

Table 5: Percent of trees with names recorded to genus level.

CREL 2010	CREL 2014	NFA	FRMP	Sal	FD SRF
39%	74%	100%	23%	100%	0%

Table 6: Most common botanical names

ID	Botanical name	freq	% of n
1	*Tectona grandis*	20559	5.6
2	*Acacia auriculiformis*	12982	3.5
3	*Shorea robusta*	11056	3.0
4	*Eucalyptus*	6445	1.7
5	*Areca catechu*	5951	1.6
6	*Dipterocarpus*	5199	1.4
7	*Syzygium grande*	4981	1.3
8	*Syzygium*	3774	1.0
9	*Acacia mangium*	3629	1.0
10	*Mangifera indica*	3322	0.9
11	*Artocarpus chama*	2719	0.7
12	*Albizia saman*	2639	0.7
13	*Heritiera fomes*	2510	0.7
14	*Artocarpus heterophyllus*	2305	0.6
15	*Cocos nucifera*	2227	0.6

Table 7: Most common genera

Rank	Genus	freq	% of n
1	*Tectona*	20426	15.8
2	*Acacia*	16789	13.0
3	*Shorea*	10708	8.3
4	*Syzygium*	9435	7.3
5	*Eucalyptus*	6854	5.3
6	*Areca*	5951	4.6
7	*Dipterocarpus*	5837	4.5
8	*Artocarpus*	5030	3.9
9	*Mangifera*	3316	2.6
10	*Samanea*	2603	2.0
11	*Swietenia*	2522	2.0
12	*Heritiera*	2510	1.9
13	*Cocos*	2227	1.7
14	*Lannea*	1951	1.5
15	*Lagestroemia*	1769	1.4

4.2 Tree dimension

The largest DBH recorded was a *Ficus benjamina* which measured 231 cm however larger trees, even those over 50cm are comparatively rare. The mean diameter is 13cm and only slightly larger at 18cm in the third quartile. Indeed only 0.5% of trees are greater than 65cm. DBH ranges across the broad forest types are largely typical of their respective areas: ranges are tighter in Sal forests which are often present as similar aged coppiced stands; larger ranges are observed in non-forest, hill forest and Bamboo/Bamboo mixed forest where species diversity is higher (see Figure 10).

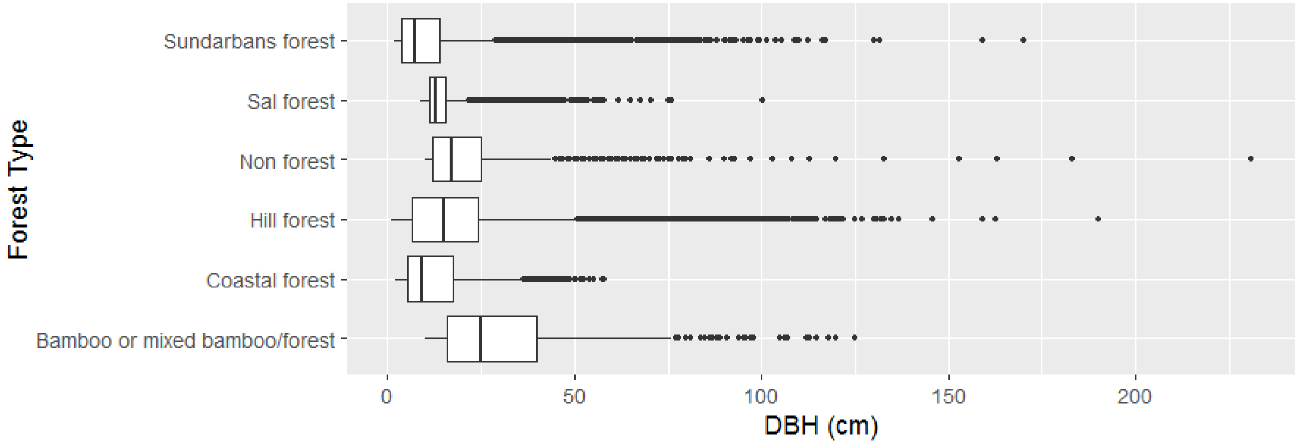

Figure 10: DBH class based on broad forest type

4.3 Development of local tree height diameter models

The best model developed and selected to estimate tree height from its diameter was a nonlinear mixed-effects model following the Gompertz form: h_m ~ 1.3 + a * exp(b * exp(c * dbh_cm)), with a random effect of the broad forest types. The details of the parameters (fixed and random effects) model AIC and standard error of the parameters are presented in Appendix 5.

The model performed very well across all forest types except for Bamboo or mixed bamboo/forest which produced a bias of 13.4. This can be explained by the high variation of this forest type which can be associated with degraded forest patches and variable tree sizes. Overall however, result are within an acceptable range producing for a total bias of 2.25. Moreover, the asymptotic curve of the model minimized over-estimation in trees with large diameters which can be a symptom of more basic linear models.

Table 8: Results of bias across forest types from the nlme model produced through R using broad forest type as a random effect variable.

Broad Forest Type	Bias (%)
Bamboo or mixed bamboo/forest	13.42364
Coastal forest	1.800363
Hill forest	2.946939
Non forest	2.785039
Sal forest	-0.24345
Sundarbans forest	1.037932
Total bias	2.255541

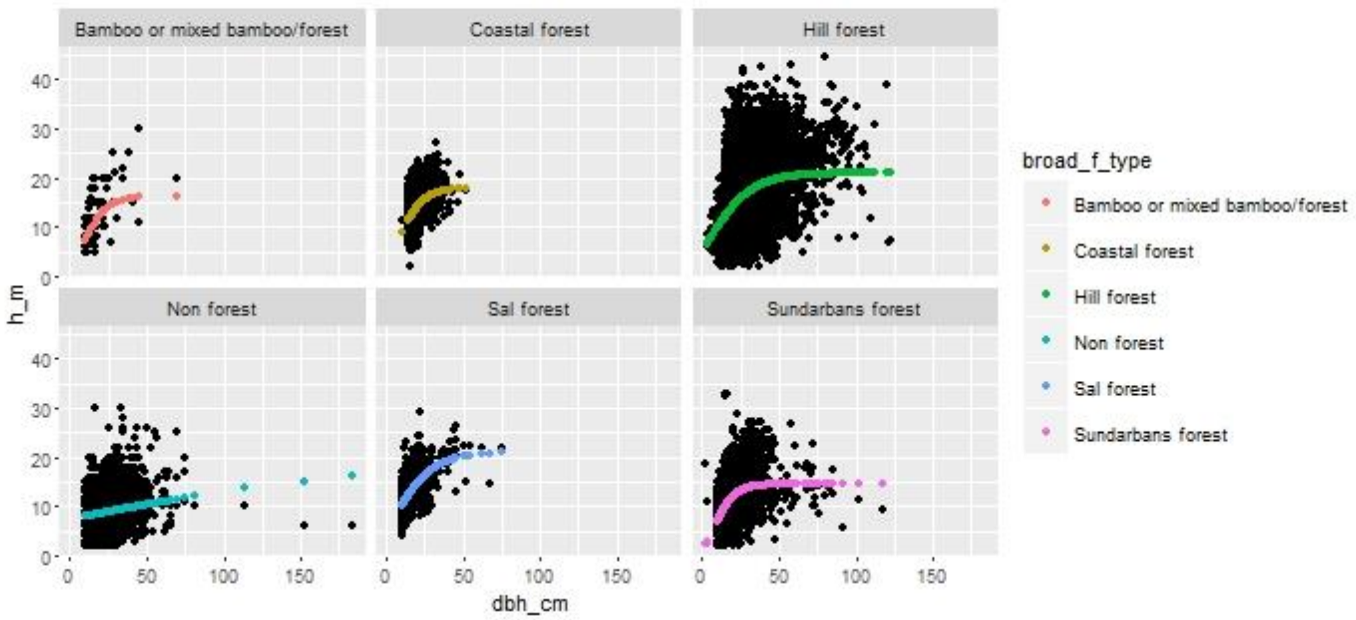

Figure 11: Fitted height-diameter model per forest type

4.4 Estimation of above-round biomass

4.4.1 Biomass at tree level

Using only DBH as the input variable, the IPCC method is more simple than the model developed by Chave et al. (2014). In its simplicity, the IPCC method provides a useful comparison to the more robust method by Chave et. al (2014).

The IPCC method produced higher results for all trees in all forest types however this was particularly significant to larger trees, an artifact of only having DBH as the input variable and the absence of height and wood density as limiting factors. The influence of the model was therefore greatest in the hill, bamboo and non-forest areas where there is a higher instance of larger trees.

The models were run again with a maximum DBH range of 65cm (accounting for 99.5% of trees) which removed large discrepancies for the largest trees, while large trees were analysed separately. Based on these observations, the Chave model was decided as the most conservative and therefore appropriate to use for AGB calculations. Moreover its performance across the broad forest types, with the local height model as a parameter for over 40% of the trees, produced predictable relationships in most areas; for example the hill forest had the highest proportion of trees with high biomass, while the village zone produced the most variability. This is typical of trees in managed environment that are often pruned or under some kind of management as opposed to unmanaged trees.

Table 9: AGB (Mg ha-1) calculated on trees with DBH less than 65cm

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA's	sd	se
chave	0.001921	5.106	27.33	111.5	115.7	5474	2441	252.09	0.42
ipcc	0.000204	7.367	34.35	153.2	145.9	6352	2441	153.2	6352

Table 10 AGB (Mg ha-1) calculated on trees with DBH greater than 65cm

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA's	sd	se
chave	170	2670	3837	4230	5212	20600	369024	2366.58	59.22
ipcc	25.77	4951	6145	7427	8648	62070	369024	4414.48	110.47

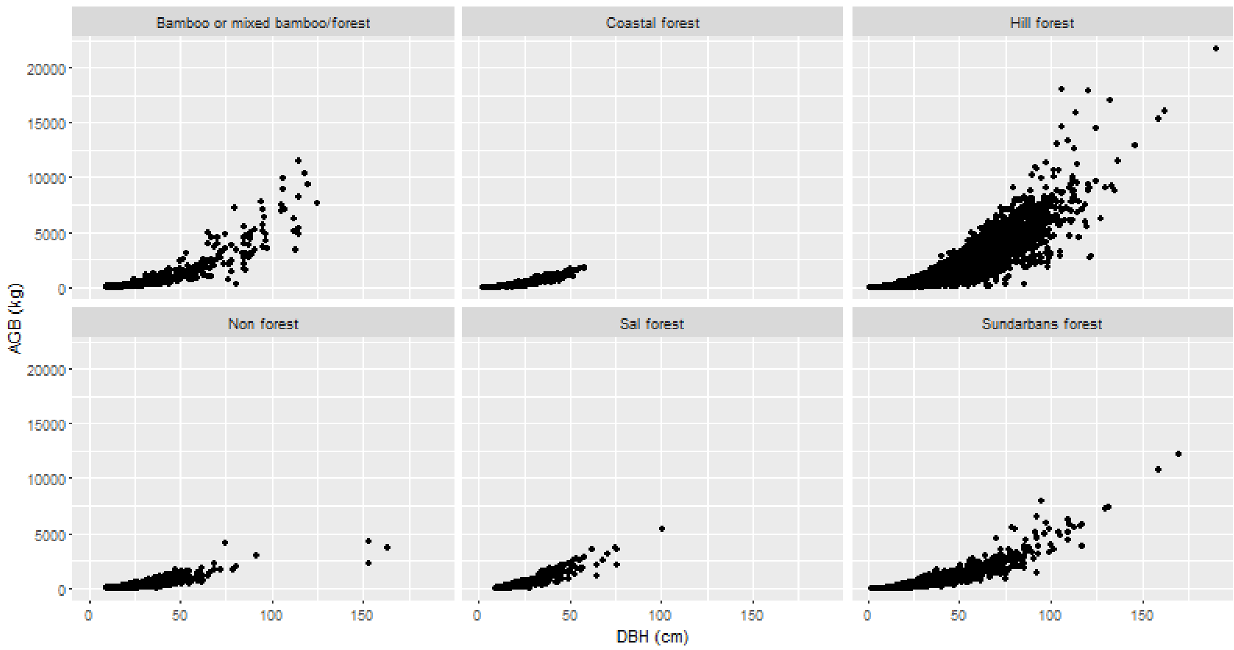

Figure 12: Tree level above ground biomass per forest type.

4.5 Estimation of emission factors under different ecological classifications

AGB was estimated across various ecological zones. It can be generally observed that larger eco-types lead to greater homogeneity and are sometimes counter intuitive. For example at the biome level, Tropical moist deciduous forest has a higher average AGB/ha than Tropical Rain Forest (TRF). This is likely explained by the highly degraded state of the hill forest areas that fall within the TRF. Similarly Analysis at the broad forest type level produced relatively low variability except for non-forest areas which were predictably low.

Table 11: AGB per FAO biome

FAO Biome	Plot Count	Ton/ha	St.dev
Tropical moist deciduous forest	5587	53.96	46.13
Tropical rainforest	3615	48.95	60.32

Table 12: AGB per FAO Biome and Forest Type

FAO Biome and Forest Type	Plot Count	Ton/ha	St.dev
TMF_plantation	490	43.58	28.18
TMF_Sal forest	3686	57.41	51.81
TMF_Sundarbans forest	1352	50.45	32.22
TRF_Hill forest	3402	50.00	61.02
TRF_plantation	120	15.32	16.60
TRF_Sal forest	59	63.82	46.19

Table 13: AGB per BFI ecological zone defined by Akhter et al 2016

BFI Zone	Plot Count	Ton/ha	St.dev
Coastal	674	40.78	33.66
Hill	3124	51.92	62.34
Village	804	55.16	66.62

Sal	3259	54.32	46.94
Sundarban	1341	50.28	31.66

Table 14: AGB per Broad Forest Type

Broad Forest Type	Plot Count	Ton/ha	St.dev
Bamboo or mixed bamboo/forest	9	55.52	51.47
Coastal forest	610	38.02	28.60
Hill forest	3405	50.24	61.36
Non forest	84	7.15	10.17
Sal forest	3744	57.52	51.71
Sundarbans forest	1352	50.34	31.87

Greater variability was observed with more specific land-use classes, in this case taken from the Bangladesh National Land Representation System. Most notably, Natural Forest Trees Area (Terrestrial) produced is associated with almost 140 t/ha, over double any other land area.

Table 15: AGB per Land Class according to the National Legend defined under the National Land Representation System.

Land Class	Plot Count	Ton/ha	St.dev
Agro-forestry	152	60.09	44.83
Beels/ Haors	1	0.11	NA
Built-up Area (Non- linear)	146	53.84	46.23
Cultivated Forest Plantation Evergreen Short Rotation (Terrestrial)	3	18.86	19.50
Cultivated Forest Plantations (Terrestrial)	3628	45.79	47.24
Cultivated Herbaceous Crops (Terrestrial)	21	15.84	24.86
Cultivated Mangrove Plantation (Aquatic)0	1	0.93	NA
Cultivated Orchards and Other Plantations-Shrub (Terrestrial)	1	58.84	NA
Cultivated Orchards and Other Plantations-Tree (Terrestrial)	10	5.25	4.46
Cultivated Shifting Crops (Terrestrial)	4	14.63	12.47
Cultivated Trees Area (Terrestrial)	44	29.01	44.23
Natural Forest Trees Area (Terrestrial)	143	138.17	102.54
Natural Herbs Dominated Area (Terrestrial)	8	38.22	25.28
Natural Hilly Forest (Terrestrial)	1075	55.62	58.49
Natural Mangrove Forest (Aquatic)	615	38.11	28.59
Natural Mixed Forest (Terrestrial)	11	52.66	47.55
Natural Plain Land Forest (Terrestrial)	1694	63.32	58.99
Natural Salt Marsh (Aquatic)	1196	47.16	26.98
Non-vegetated Area	11	1.25	1.30
Rural Settlement	7	36.45	45.11
Soil, Sand Deposit	1	17.26	NA

5 CONCLUSIONS AND RECOMMENATIONS

The estimation of forest biomass involves numerous steps including field data collection, data cleansing, data processing, the development of models, the selection of appropriate allometric equations and finally data analysis and reporting. At each step, there are numerous potential sources of error and bias. The harmonization of this study demonstrated many of these sources.

Data entry errors

Data collection and entry errors can render some records unusable. Utilising modern technologies such as electronic data collection devices can reduce these kinds of errors by employing validation rules so data is vetted during the collection process.

Incorrect or missing botanical information affected almost one quarter of all trees. Species identification is a key determinant of wood density and has significant implications for biomass assessments. In the absence of accurate species identification, generic values must be used for both wood density and allometric equations used to estimate volume and biomass which in turn reduce the confidence of estimates. In Bangladesh there is significant scope for the development of local values and equations for important species.

Problems associated with land cover classes

The interoperability of land cover information is a common issue that arises when attempting to monitor or assess change in land systems across different data sources. Land cover classes are generally developed to meet specific project objectives without consideration of potential comparability. Furthermore the definitions behind class names that would facilitate their comparability are often insufficient, not defined or missing when attempts are made to retrospectively use the data for the purpose of change detection. In this report we harmonized land cover classes of the various inventories in line with the National Land Cover Reference System of Bangladesh. This process required broad assumptions of definitions behind those classes due to an absence of documentation or detailed definitions. The result is that much of the data must be assigned to broad classes which limits their application for deeper analysis that greater specificity would provide. It also presents a source of bias within the data. For example, the biomass estimates following LCCS categories reflected better variations of carbon stock between categories, compared to broad forest types, where biomass estimates were not very different between types with very large standard deviations. This process also highlights the necessity for robust archiving protocols of historic data that facilitate reinterpretation to ensure future analysis can be performed.

The Land Cover Classification System (LCCS) described by Di Gregorio and Jansen (1998) presents an emerging approach that addresses the lack of comparability of traditional classification systems through an ‘object oriented approach’ of land cover class description. In this approach classes defined in the field do not rely on broad descriptions such as ‘forest’ or ‘grass land’, but describe the physical components of a land feature as they are observed. Such detailed descriptive information forms the basis of a Land Cover Meta Language that can be reinterpreted to fit any classification system at any stage. An example of LCCS descriptions is provided in Appendix 5.

Problems associated with AGB estimates

The use of broad forest types was useful in establishing tree height –diameter relationships, the association was less effective when estimating biomass on a per hectare basis. Bamboo or mixed bamboo/forest, Hill, Sal and Sundarban forest were all within a 5% difference, while only Non forest and Coastal forest presenting significant differences. To more effectively derive variations in forest biomass stocks, the use of variables related to degradation is necessary. This is notably demonstrated by the Natural Forest Trees Area (Terrestrial) land use class where the average Ton/ha is more than twice that of the second highest value (Natural Plain Land Forest (Terrestrial) which is also commonly associated with Sal forest) according to the land use classes defined under the national reference system.

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Appendix 1. Historical Inventories

Table 16: Adapted from Akhter (2013).

Year	Title	Institutions involved	Ground Inv.	Remote Sensing (year)	Scale of Interpretation	Country Coverage	Thematic cover
1773		Messrs. Ritchie, Richards and Martain	1769-1773			Sundarban	includes waterways
1829		Lt. Prinsep, Lt. Hodges	1821-1823 and 1829			Sundarban – produced map (scale: 0.5 inch = 1 mile)	boundaries between forest and cultivated
1873		Mr. Ellison	1851-55 1855-59			Sundarban – 24 Parganas districts and Khulna, Begerhat, Satkhira. produced map (scale 0.25 inch=1 mile)	Revenue surveys
1909		Survey Dept. District of Bengal	1905-09			Sundarban. produced map (scale 1 inch= 1 mile)	
1924		Mr. Curtis				Sundarban – map scale 1:31,380	Loss of area through erosion – Growing stock
1960		FORESTAL (Forestry and Engineering International Limited)	1958-59	1958	aerial photography	Sundarban –set of maps (scale 2 inches = 1 mile)	wood supply for proposed newsprint mill at Khulna – forest cover maps- volume, yields,
1961	Inventory Project of Sangu-Matamuhari reserve forests - Timber extraction by mechanical means from Chittagong Hill Tracts		1961	1958	aerial photos	Chittagong Hill – Sangu and Matamuhuri Reserve Forests	Produced Working plan for Sangu and Matamuhuri reserve forests for the period 1967-68 to 1986-87
1964		Hunting Survey Corporation Limited of Canada –	1961-63	1961	aerial photos – 1:15,840	Hill Forests – Kassalong and Rankhiang Reserve Forests	Produced stand and stock tables. Topo maps at 1:15,840 and forest cover
1980-81	"Village Forest Inventory" – FAO/UNDP Project BGD/78/020 and BGD/78/017	Mr. Hammermaster	1980-81			267 village units (all Districts except Chittagong Hills)	Growing sotck of village forests and bamboo, non-wood value trees
1984		Overseas Development Administration (ODA)	1983-84		aerial photography 1981	Sundarban – forest type maps (scale 1:50,000); incidence of top dying of Sundri species (scale	main species, stems per ha., mean and total volume. Stand

1984	FAO/UNDP Project BGD/79/017		1982-84			Sitapahar Reserve	Forest type: plantations and natural forests
1984	FAO/UNDP BGD 75/071	FAO/UNDP	1982-84	1984	aerial photographs (1:30,000)	Chittagong, Cox's Bazar	
1984	FAO/UNDP Project BGD/79/017 "Assistance to the Forestry Sector of Bangladesh"		none	1984	aerial photos at 1:15,000	Hill Forests – Kassalong and Rankhiang Reserve Forests	identification of changes from data from 1963
1984		Forest Inventory Division of the Forest Research Institute -	1981-82			Pulpwood Plantation: Kaptai	Area, stocking, major species.
1984	FAO/UNDP Project BGD/79/017		none	1984	aerial photos at 1:50,000	Sangu and Matamuhuri Reserve Forests	Forest type delineation: (i) shifting cultivation (ii) seemingly exploitable
1985	Inventory of the mixed hardwood-teak plantations		1982-85	1982	aerial photos	Plantations: Chittagong and Cox's Bazar Forest Divisions	Area by stratum groups and age classes, stock.
1986	SPARRSO – Land Accretion and Plantation Map		1986	1984	aerial photographs (1:50,000)	Mangrove Plantation – Coastal Afforestation. Produced 64 sheets at 1:10,000	Area, stocking, growth of the maturing mangrove stands
1986			1984-85	1982, 1984	aerial phoots: 1:50,000; 1:15840	High Forest: Chittagong and Cox's Bazar Forest Divisions	Area, Number of trees per ha. (dbh classes),
1987	Map series: "Forest Cover Map of the Southern part of Sylhet Forest Division" (24 sheets at 1:15,840)		1986-87	1984-87	1:50,000 (40% of plantation forests); SPOT satellite images	Sylhet Forest Division	Forest extent, plantations, bamboo.
1997	Spot Satellite Forest Cover Mapping – GOB/WB Forest Resources Management Project	Sustainable Ecosystems International, Corp. Philippines.	Field verification: 1997	1996	Spot images at 1:50,000 Bands: 1 (0.5-0.59 µm) 2 (0.61-0.69 µm) 3 (0.79-0.89 µm) Ground Resolution: 20x20 mt.	Sylhet forest Division	NF, PL, Reed Forest, Non-forest areas
1998	Forest Resources Management Project (FRMP) - Forest Inventory of the Natural Forests and Forest plantations	Mandela Agricultural Development Corporation and Forest Department, World Bank	1995-1996	1996	aerial photos (1:15,000)	Sundarban, CoxsBazar, Chittagong forest division	NF, PL, FAC, TV, CV, FO

2001	Forest Inventory of the Sal Forests of Bangladesh	Forest Department	1999-2000			Sal Forests of Central and Northwest Bangladesh (Dhaka,	Species, dbh, height, regeneration,
2007	National Forest and Tree Resources Assessment 2005 - 2007	Forest Department and Space Research and Remote Sensing Organization (SPARRSO)	2006	2004-06	Landsat TM	Bangladesh	Land use,
2009	Sundarban Carbon inventory					Sundarban reserved forests	
2010	Carbon Inventory for 6 PAs	Forest Department/ BRAPA Project under USAID	2010	2011		6 PAs (Teknaf WS, Inani, Medhakachhapia KNP, Fashiakhali WS, Dudpukuria-Dhopachari WS & Sitakunda)	
2014	Forest Carbon Inventory at eight Protected Areas (PAs) in Bangladesh	Forest Department/CREL 2014 Project under USAID	2014	2014			

Appendix 2. Land Classes per inventory

Project	Land use classes
FRMP (1997)	Agriculture Bush-shrubland Coastal forest Forest plantation Fruit-other trees Natural hill forest No vegetation Settlement Tidal forest
FD-SAL (2001)	Agroforestry Grass - degraded former forest land Immature sal forest 1.5 - 5.0m Mature Sal Forest Private - Encroached Woodlot Young re-growth of sal - less than 1.5 m
FD-NFA (2007)	**Forest** Forest with natural or natural assisted regeneration Broad-leaved forest Hill forest Sal forest Swamp forest (freshwater) Mangrove forest (saltwater) Bamboo or mixed Bamboo/broad-leaved forest Forest plantations Long rotation forest plantation: 40-60 years (Teak, Dipterocarp, Sal, Jam, etc.) Short/medium rotation forest plantation: 10-20 years (Acacia, Eucalyptus, Gamar, etc.) Mangrove plantation Rubber plantation Other wooded lands Shrubs (or shrubs/trees) Swamp with shrubs (or shrubs/trees) **Other land** Natural and semi natural land Barren land/Grassland **Cultivated and managed land** Annual crop Without or with low tree cover With tree cover; 0,1 – 0,5 ha With tree cover; >0.5 ha **Perennial crop** Without or with low tree cover With tree cover; 0,1 – 0,5 ha With tree cover; >0.5 ha Rangeland/Pasture Wooded land with shifting cultivation (fallow) **Artificial areas** Urban settlements **Rural settlements** Without or with low tree cover With tree cover; 0,1 – 0,5 ha With tree cover; >0.5 ha Highways and other artificial areas **Inland water** Haor & Baor Lakes Rivers Ponds
FD-SRF (2010)	Intact Forest, Degraded Forest, Deforested, Scrub (<5 m height), Grass/Bare Ground

BRAPA (2010)	Agriculture Agriculture and settlement Bamboo Degraded Forest Degraded Forest (<40% cover) Dense Forest Grass/Bare Ground Others Plantation Plantation (LR) Plantation (SR) Settlement (villages) Settlement, Agriculture Waterbody
CREL (2014)	Agriculture Bare Land Degraded forest Forest Plantation Rubber Settlement Tea Garden

Appendix 3. Harmonisation of Land Classes

Project	Original Land use	LCCS code	LCCS Description
CREL 2010	Agriculture	CH	Cultivated Herbaceous Crops (Terrestrial)
CREL 2010	Agriculture and settlement	RS	Rural Settlement
CREL 2010	Bamboo	FM	Natural Mixed Forest (Terrestrial)
CREL 2010	Degraded Forest	F	Natural Forest Trees Area (Terrestrial)
CREL 2010	Degraded Forest (<40% cover)	F	Natural Forest Trees Area (Terrestrial)
CREL 2010	Dense Forest	F	Natural Forest Trees Area (Terrestrial)
CREL 2010	Grass/Bare Ground	NA	NA
CREL 2010	Others	NA	NA
CREL 2010	Plantation	CT	Cultivated Trees Area (Terrestrial)
CREL 2010	Plantation (LR)	FP	Cultivated Forest Plantations (Terrestrial)
CREL 2010	Plantation (SR)	FP	Cultivated Forest Plantations (Terrestrial)
CREL 2010	Settlement (villages)	RS	Rural Settlement
CREL 2010	Settlement, Agriculture	RS	Rural Settlement
CREL 2010	Waterbody	W	Water
CREL 2014	Agriculture	CH	Cultivated Herbaceous Crops (Terrestrial)
CREL 2014	Bare Land	SSd	Soil, Sand Deposit
CREL 2014	Degraded forest	F	Natural Forest Trees Area (Terrestrial)
CREL 2014	Forest	F	Natural Forest Trees Area (Terrestrial)
CREL 2014	Plantation	FP	Cultivated Forest Plantations (Terrestrial)
CREL 2014	Rubber	CT	Cultivated Trees Area (Terrestrial)
CREL 2014	Settlement	RS	Rural Settlement
CREL 2014	Tea Garden	OS	Cultivated Orchards and Other Plantations-Shrub (Terrestrial)
FRMP	Agriculture	CH	Cultivated Herbaceous Crops (Terrestrial)
FRMP	Bush-shrubland	S	Natural Shrubs Dominated Area (Terrestrial)
FRMP	Coastal forest	NMF	Natural Mangrove Forest (Aquatic)
FRMP	Forest plantation	FP	Cultivated Forest Plantations (Terrestrial)
FRMP	Fruit-other trees	OT	Cultivated Orchards and Other Plantations-Tree (Terrestrial)
FRMP	Natural hill forest	FEh	Natural Hilly Forest (Terrestrial)
FRMP	No vegetation	A	Non-vegetated Area
FRMP	Settlement	RS	Rural Settlement
FRMP	Tidal forest	SM	Natural Salt Marsh (Aquatic)
NFA	Bamboo or mixed Bamboo/broad-leaved forest	FM	Natural Mixed Forest (Terrestrial)
NFA	Haor & Baor	BH	Beels/ Haors
NFA	Highways and other artificial areas	AS	Artificial Surfaces
NFA	Hill forest	FEh	Natural Hilly Forest (Terrestrial)
NFA	Long rotation forest plantation: 40-60 years (Teak, Dipterocarp, Sal, Jam, etc.)	FP	Cultivated Forest Plantations (Terrestrial)
NFA	Mangrove forest (saltwater)	NMF	Natural Mangrove Forest (Aquatic)
NFA	Mangrove plantation	FMp	Cultivated Mangrove Plantation (Aquatic)
NFA	Ponds	Po	Ponds

NFA	Rangeland/Pasture	H	Natural Herbs Dominated Area (Terrestrial)
NFA	Rivers	R	Rivers
NFA	Short/medium rotation forest plantation: 10-20 years (Acacia, Eucalyptus, Gamar, etc.)	FPes	Cultivated Forest Plantation Evergreen Short Rotation (Terrestrial)
NFA	Shrubs (or shrubs/trees)	S	Natural Shrubs Dominated Area (Terrestrial)
NFA	Urban settlements	BNl	Built-up Area (Non- linear)
NFA	With tree cover; >0.5 ha	CT	Cultivated Trees Area (Terrestrial)
NFA	With tree cover; 0,1 – 0,5 ha	CT	Cultivated Trees Area (Terrestrial)
NFA	Without or with low tree cover	A	Non-vegetated Area
NFA	Wooded land with shifting cultivation (fallow)	SC	Cultivated Shifting Crops (Terrestrial)
Sal	Agroforestry	AF	Agro-forestry
Sal	Grass - degraded former forest land	H	Natural Herbs Dominated Area (Terrestrial)
Sal	Immature sal forest 1.5 - 5.0m	FDp	Natural Plain Land Forest (Terrestrial)
Sal	Mature Sal Forest	FDp	Natural Plain Land Forest (Terrestrial)
Sal	Private - Encroached	BNl	Built-up Area (Non- linear)
Sal	Woodlot	FP	Cultivated Forest Plantations (Terrestrial)
Sal	Young re-growth of sal - less than 1.5 m	FDp	Natural Plain Land Forest (Terrestrial)
NA	NA	NA	NA

Appendix 4. Tree species by broad forest type

Bamboo		
Botanical name	Total	Percent
Dipterocarpus turbinatus	77	8
Lannea coromandelica	67	7
Schima wallichii	63	7
Gmelina arborea	58	6
Ficus hispida	50	5
Discladium squarrosum	44	5
Stereospermum chelonoides	41	4
Cocos nucifera	39	4
Albizia procera	37	4
NA	34	3.6

Hill		
Botanical name	Total	Percent
Tectona grandis	20058	20
Dipterocarpus sp.	5199	5
Syzygium grande	4946	5
Acacia auriculiformis	4637	5
Eucalyptus sp.	4559	5
Syzygium sp.	3765	4
Acacia mangium	2943	3
Artocarpus chama	2152	2
Lagerstroemia speciosa	1942	2
NA	28997	28

Mangrove		
Botanical name	Total	Percent
Heritiera fomes	2506	64.4
Excoecaria agallocha	1185	30.4
Xylocarpus moluccensis	124	3.2
Avicennia officinalis	31	0.8
Aglaia cucullata	13	0.3
Luffa cylindrica	7	0.2
Shirakiopsis indica	6	0.2
Pothos scandens	4	0.1
Xylocarpus granatum	4	0.1
Sonneratia apetala	3	0.1
NA	0	0

Non-forest		
Botanical name	Total	Percent
Areca catechu	5927	19.4
Mangifera indica	2953	9.7
Albizia saman	2586	8.5
Cocos nucifera	2127	7.0
Artocarpus heterophyllus	1940	6.3
Swietenia mahagoni	1638	5.4
Phoenix sylvestris	1552	5.1
Lannea coromandelica	913	3.0
Albizia procera	737	2.4
Borassus flabellifer	692	2.3
NA	131	0.4

Mangrove planation		
Botanical name	Total	Percent
Avicennia officinalis	5	71.4
Sonneratia apetala	2	28.6
NA	0	0

Plantation		
Botanical name	Total	Percent
Tectona grandis	242	44
Gmelina arborea	86	15.6
Ficus hispida	30	5.5
Dalbergia sissoo	28	5.1
Eucalyptus camaldulensis	26	4.7
Albizia saman	17	3.1
Albizia procera	15	2.7
Acacia nilotica	12	2.2
Lannea coromandelica	10	1.8
Swietenia mahagoni	6	1.1
NA	5	1

Appendix 5. LCCS Example

The classification of objects within an LCCS feature class are categorized into three broad classes: Vegetated, Non-vegetated and Water. Under these descriptions, additional attributes may be added to provide more detail at different hierarchical levels as shown in Table 17.

Table 17: Land features are described at different hierarchical levels (Taken from the BFD (2016)).

Land feature description process	**Land Feature 1**	**Land Feature 2**	**Land Feature 3**
LAND FEATURE DETAILS Land Feature ID, Size of Land Feature Area, Owner Group,Issues, Leaf Cover, CrownCover, photos and other general descriptions	Size> 5ha, management: unmanaged, linear form, water, pollution	Size<5ha, Owners Group: Individuals, Leaf Cover, Canopy cover: 20-30%	Size>5ha, Owner group: Community, Canopy cover, 80-100%, Leaf cover: 70%
OBJECT TYPE Vegetated, Non-vegetated and Water	Water	Vegetated and Non-vegetated	Vegetated
OBJECT ATTRIBUTES Vegetated: Trees, shrubs, grasses/herbs Non-vegetated: Linear, Nonlinear, bare ground, dump site etc. Water: river, canal, stream, lake, pond	River	Vegetated: Trees Non-vegetated: Building/structure	Trees
ARTIFICIALITY (OBJECT ATTRIBUTES)	Natural/ Semi-natural	Cultivated	Cultivated
ATTRIBUTE DETAILS Trees: Artificiality, Growth Form/Age, Management, Rotation Shrubs: Management Grasses/herbs: Crop, cropping pattern, management Non-vegetated: Comments required River: Salinity Lake: Salinity Pond: Salinity	Fresh	Trees: Cultivated and managed Non-vegetated: Private houses	Trees: Cultivated and managed Management: Plantation, Treatment: Selective felling, Rotation: 10-15 years

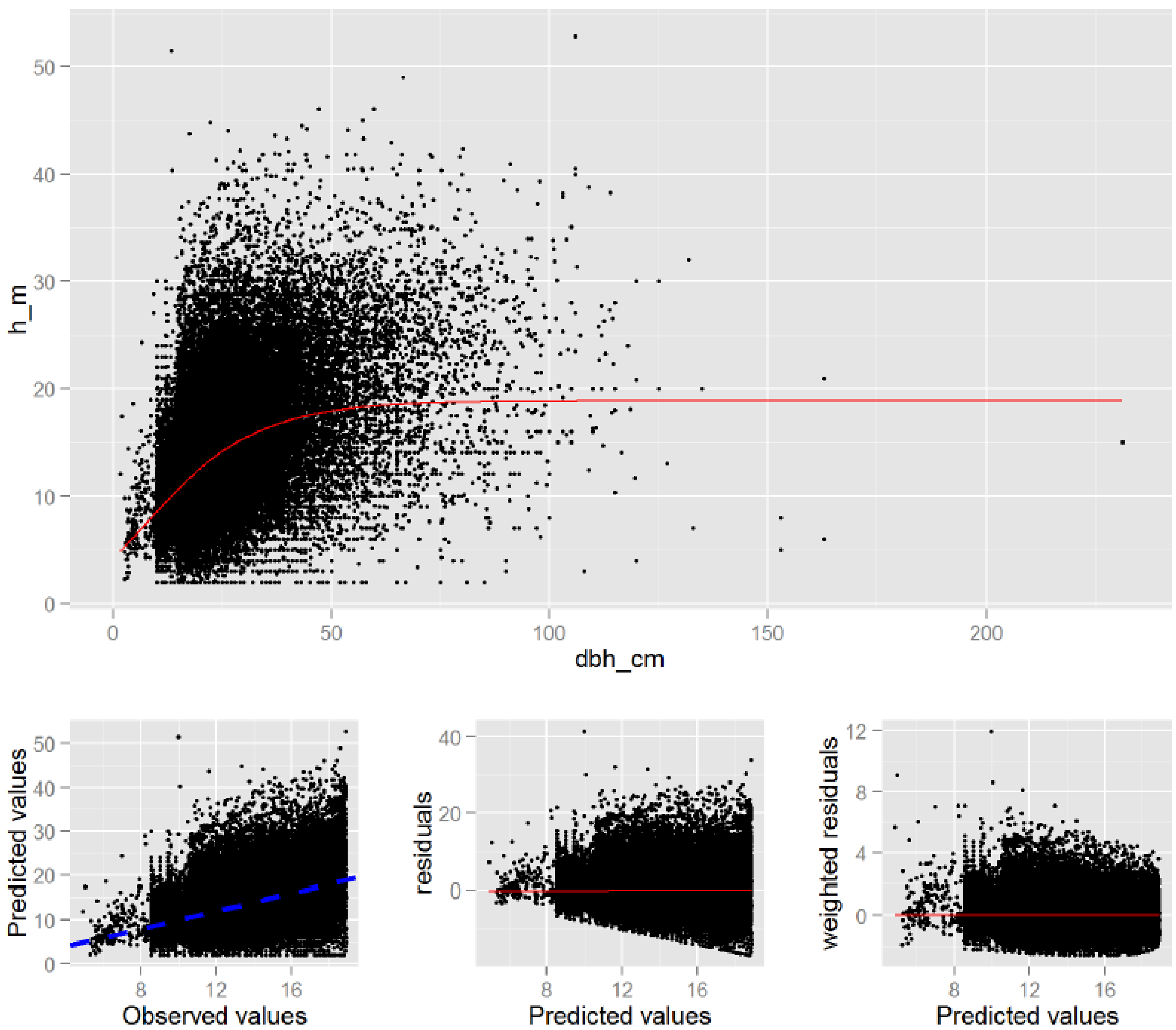
Appendix 6. Results of Height-Diameter Model

The Gompertz model was compared across three mixed-effect scenarios using the nlme package in R. Model 1 used no mixed effect while Models 2 and 3 use the FAO Biome and the broad forest type respectively. The mixed-effect had a positive influence in both cases but more so for the broad forest type which equated the lowest AIC of the three models. The comparison shown that the use of biophysical and geographic mixed effect parameters can improve tree height estimates in the case trunk diameter has been measured.

No Mixed Effect

Model characteristics	
Formula	h_m ~ 1.3 + a * exp(b * exp(c * dbh_cm))
N_parameters	3
N_observations	107789
start	15 -2 -0.1
ranef_variable	NA
residual_function	varPower
residual_coeff	0.4812095
AIC	627294

Fixed parameters	**a**	**b**	**c**
starting values	15	-2	-0.1
Model parameters	17.591	-1.7651	-0.0687
p_values	0	0	0.00064
se	2.51174	0.56464	0.0356



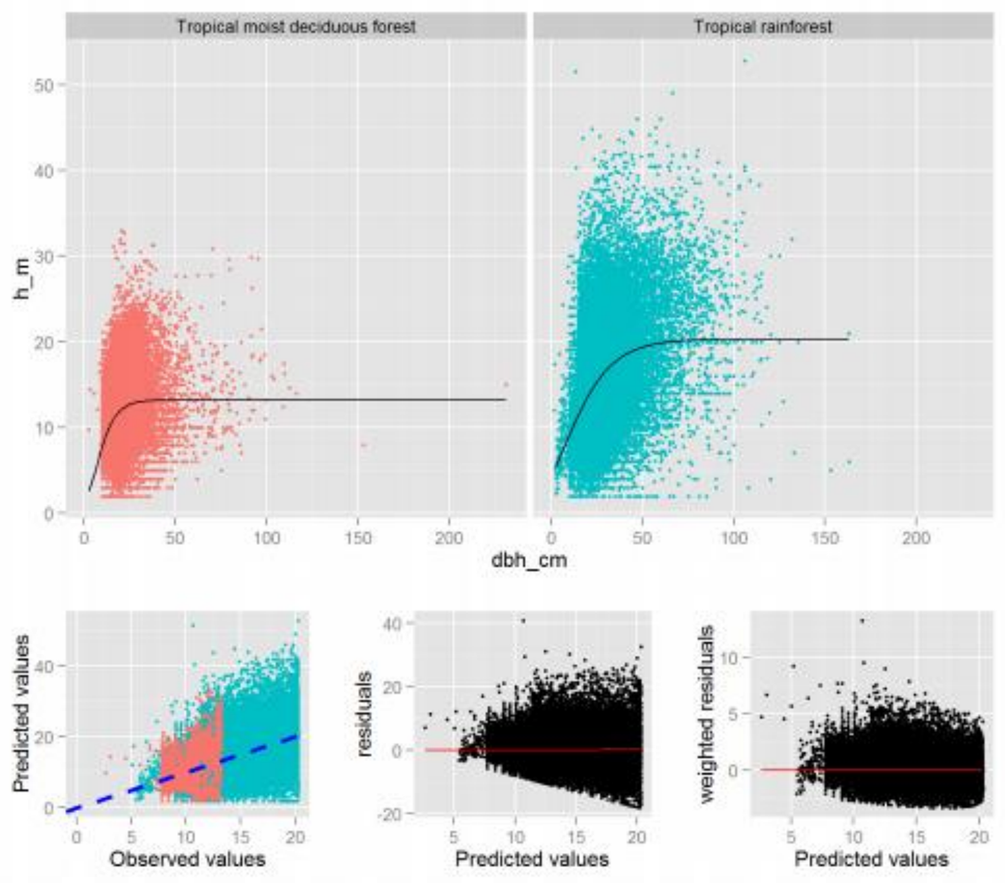
h_m
dbh_cm
0
10
20
30
40
50
0
50
100
150
200
Predicted values
Observed values
residuals
Predicted values
weighted residuals
Predicted values
8
12
16

FAO Biome as Mixed Effect

Model characteristics	
Formula	h_m ~ 1.3 + a * exp(b * exp(c * dbh_cm))
N_parameters	3
N_observations	107789
start	15 -2 -0.1
ranef_variable	fao_biome
residual_function	varPower
residual_coeff	0.4344926
AIC	621609.8

Fixed parameters	a	b	c
starting values	15	-2	-0.1
Model parameters	15.4589	2.61827	0.121472
p_values	0	0	0.00064
se	2.51174	0.56464	0.0356

Random effect parameters	a	b	c
Tropical moist deciduous forest	-3.55045	-0.797712	-0.050318
Tropical rainforest	3.550447	0.7977124	0.0503178

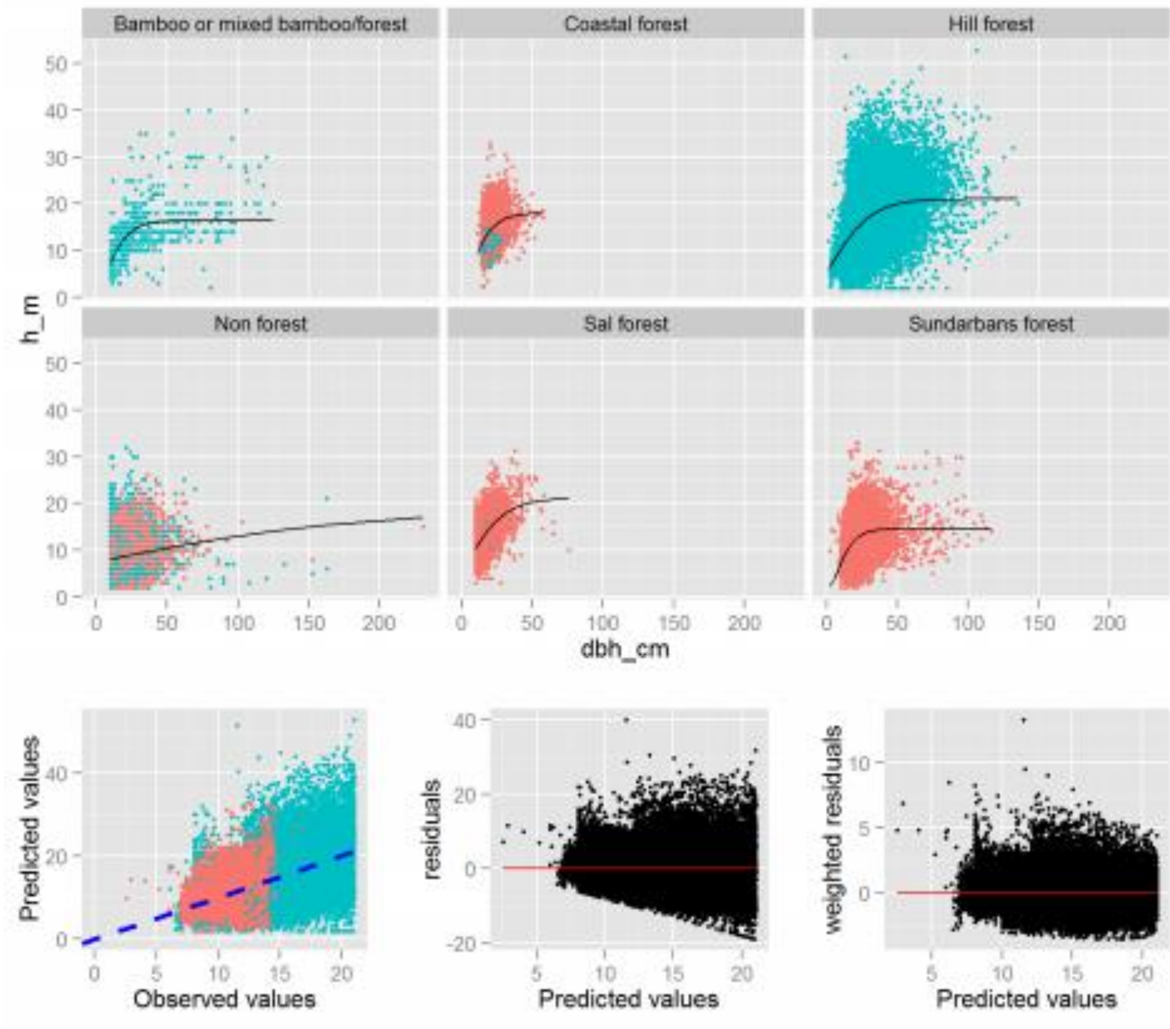


Broad Forest Type as Mixed Effect

Model characteristics	
Formula	h_m ~ 1.3 + a * exp(b * exp(c * dbh_cm))
N_parameters	3
N_observations	107789
start	17.5 -1.8 -0.07
ranef_variable	broad_f_type
residual_function	varPower
residual_coeff	0.4241396
AIC	602448.5

Fixed parameters	**a**	**b**	**c**
starting values	17.5	-1.8	-0.07
Model parameters	17.1266	2.16646	0.084394
p_values	0	0	0.00064
se	2.51174	0.56464	0.0356

Random effect parameters	**a**	**b**	**c**
Bamboo or mixed bamboo/forest	-1.959995	-0.612063	-0.026718
Coastal forest	-0.407111	-0.430811	-0.028663
Hill forest	2.6160295	0.5973383	0.0189476
Non forest	0.8019318	1.0954432	0.0752457
Sal forest	2.7974976	0.5836318	0.0160649
Sundarbans forest	-3.848353	-1.233539	-0.054878



Bamboo or mixed bamboo/forest
Coastal forest
Hill forest
Non forest
Sal forest
Sundarbans forest
h_m
dbh_cm
Predicted values
Observed values
residuals
Predicted values
weighted residuals
Predicted values